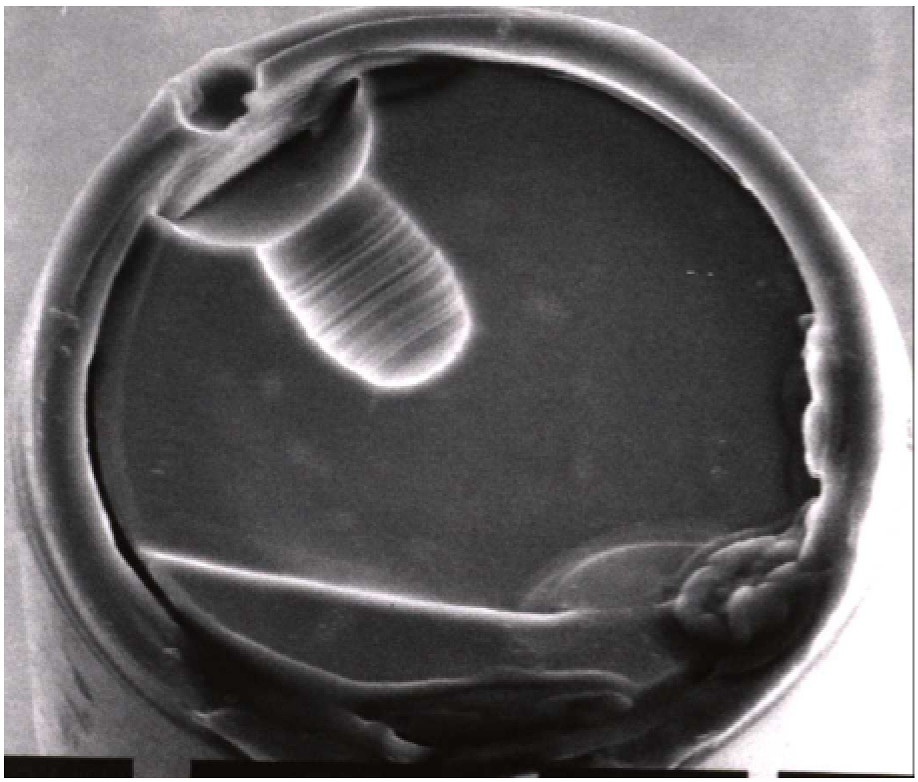
ISS Fiber Optic Failure Investigation

Root Cause Report

August 1, 2000



ISS Fiber Root Cause Investigation Team
Lead organization NASA GSFC
Sponsored by: NASA JSC and the Boeing Company

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"In this work, when it shall be found that much is omitted, let it not be forgotten, that much likewise is performed…"

Samual Johnson, A.M.
For the last paragraph of Preface to his two-volume *Dictionary of the English Language*, Vol. 1, page 5, 1755, London, Printed by Strahan.

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Executive Summary

In August of 1999, Boeing Corporation (Boeing) engineers began investigating failures of optical fiber being used on International Space Station flight hardware. Catastrophic failures of the fiber were linked to a defect in the glass fiber (see Figure 1, "Rocket Engine Defect"). Following several meetings of Boeing and NASA engineers and managers, Boeing created and led an investigation team, which examined the reliability of the cable installed in the U.S. Lab. NASA Goddard Space Flight Center's Components Technologies and Radiation Effects Branch (GSFC) led a team investigating the root cause of the failures. Information was gathered from: regular telecons and other communications with the investigation team, investigative trips to the cable distributor's plant, the cable manufacturing plant and the fiber manufacturing plant (including a review of build records), destructive and non-destructive testing, and expertise supplied by scientists from Dupont, and Lucent-Bell Laboratories. Several theories were established early on which were not able to completely address the destructive physical analysis and experiential evidence. Lucent suggested hydrofluoric acid (HF) etching of the glass and successfully duplicated the "rocket engine" defect. Strength testing coupled with examination of the low strength break sites linked features in the polyimide coating with latent defect sites. The information provided below explains what was learned about the susceptibility of the pre-cabled fiber to failure when cabled as it was for Space Station and the nature of the latent defects.

1.0 INTRODUCTION

This report presents the work done to understand the "rocket engine" defects found in optical cable being used by the International Space Station and to understand their impact on the cable's reliability for use in space. Detailed information is given about:

- The failure of optical cable used for the International Space Station
- Techniques which can be used to inspect for the presence of "rocket engine" defects and coding defects
- The ability of the manufacturers of the fiber and cable to supply cable within the specification limits
- The suitability of the governing specification for this cable.
- Important manufacturing processes and material interactions which support HF generation from fluoropolymer cable components
- The affect of the manufacturing processes used to make NFOC-2FFF-1GRP-1 on its reliability
- The nature of the low break strength found for this cable

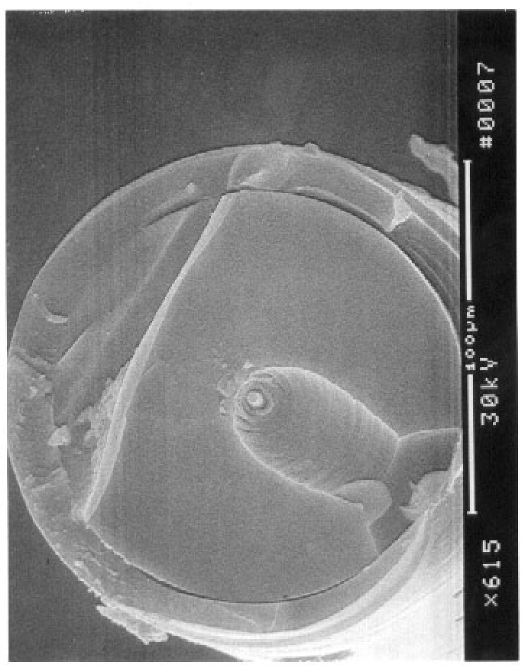
The members of Team 2, who generated this report and other contributors, are listed in Section 12.0. Conclusions and recommendations are summarized at the end of the report.

2.0 BACKGROUND

In mid-1999 Boeing engineers were finding multiple failures of 1999 vintage NFOC-2FFF-1GRP-1 optical cable being used to fabricate harnesses for the International Space Station (ISS) program. This cable was used in U.S. Laboratory module, an element of the International Space Station, a deliverable under contract NAS15 10000. Not only were fiber breaks being detected during handling, but breaks were found over time with no handling (sitting on the shelf). This was believed to be a much different experience than was encountered during population of the U.S. Lab module with 6982 feet [ref-1] of 1996 vintage cable of the same part number. The Boeing materials and processes engineers performed destructive physical analysis (DPA) on the fiber at the break locations. Figure 1 shows one of the first images resulting from the DPA. The cone and bulb shape of the defect earned it the name "rocket engine". This description replaced the term "bubble" which according to the fiber manufacturer, is associated with a topology that is unique and not represented by Figure 1.

Efforts were immediately made by Boeing and NASA Goddard Space Flight Center (GSFC) personnel to investigate optical inspection methods being used, to uniquely identify the stock of cable involved, and to expand the number and types of DPA images of the defect and the surrounding fiber and cable elements.

A summit was called by Boeing in October 1999 and included engineers and scientists from: various Boeing organizations (KSC, Huntington Beach, JSC), the NASA ISS parts control board, the NASA GSFC Component Technologies and Radiation Effects Branch, the cable manufacturer (BICCGeneral, formerly Brand Rex), the fiber manufacturer (Spectran Specialty Optics, now Lucent Specialty Fiber Technologies), and The Aerospace Corporation. During the summit the following overview was presented: the failure found, methods used to detect the failures, the manufacturing processes and fault trees produced by Boeing. Theories about the root cause were discussed and a plan was drafted, to initiate a formal root cause investigation, to determine the reliability of the cable installed in the U.S. Lab and to determine whether more of the same cable should be made for space flight use. Boeing retained the leadership for the latter portion of the investigation and assigned NASA GSFC the lead of the root cause investigation. This was done with NASA GSFC's concurrence and NASA JSC's concurrence and funding support. The attendees of the summit became the core of the combined investigation team.



Courtesy of The Boeing Company

Figure 1 "Rocket Engine" Defect

The investigation plan included a review of the processes used by the cable distributor (Sea Wire and Cable), the cabler and the fiber manufacturer. A review of process data was performed to identify significant changes that may have contributed to the root cause. Research and experiments were also performed in support of the root cause investigation by several of the participating organizations. A preliminary review of the current cable specification was done. Strength testing was performed by Boeing in support of the cable reliability investigation. Weekly telecons were held to review the emerging information and to formulate upcoming activities. Experts from Dupont and Lucent-Bell Laboratories were invited to participate to assist in analysis of the test results being collected and to guide emerging hypotheses. Lucent-Bell Laboratories also conducted testing for the investigation.

A web site was established for the team. All photographs and documents being distributed throughout the team were posted there. A password protection system was put in place to limit access to only team members and to protect manufacturer's proprietary information.

The presentation of the hypothesis by Lucent-Bell Laboratories, which proposed that the root cause of the defect was hydrofluoric acid (HF) etching and their subsequent duplication of the defect using HF, was a turning point in the investigation. Subsequent activities focused on understanding the circumstances, both chemically and environmentally, which would support etching of the glass in this way. By understanding the conditions, which would support HF etching of the glass fiber, the failure causing defects could be identified. The team also started to consider the manufacturability of cable without these defects and/or methods, which could be used to screen them out.

In parallel with the research on the HF etching mechanism, Boeing wrote a test plan and constructed the test equipment to conduct strength testing of fiber from lots of the same manufacturing period associated with the installed cable. The intention was to make a life expectancy prediction using a statistical parameter, which determines the life of glass which ages due to stress corrosion. The lifetime prediction would also consider the stress and temperature conditions the installed fiber will experience due to how it was installed within the cable and within the spacecraft structure, the stresses associated with launch, and the presence of a moist ambient environment in space. Testing was performed on fiber that was still contained in the cable (finished product) and though the data did not clearly provide a quantifiable reliability number, it did show that even after the "rocket engine" defects were screened out, the fiber had low break strength. End faces of the cabled fibers, which broke at low strength, were inspected and they all featured a characteristic bubble-like feature in the polyimide coating and bare glass surfaces, which have been etched or corroded. This evidence is believed to indicate that discontinuities in the fiber coating are allowing both the "rocket engine" etch pit and low strength associated with moisture enhanced stress corrosion.

A second summit was held by Boeing in February 2000 to summarize the progress made by the team, to formulate a plan for future use of the installed cable and to plan for the purchase of new cable. New teams were established for the following action areas: 1) cable redesign, specification rewrite and cable qualification, 2) Root cause wrap-up, 3) Maintenance plan for on-orbit repair inside the module, 4) Maintenance plan for extra-vehicular on-orbit repair, and 5) Plan for a shuttle mission experiment to understand in-flight risks associated with this cable. This report is the final deliverable for Team 2.

3.0 CABLE HISTORY

3.1 The Specification

The optical cable being used by Boeing on ISS is governed by the NASA specification SSQ 21654, "Cable, Single Fiber, Multimode, Space Quality, General Specification for". The custodian of the specification is McDonnell Douglas Space Systems Company in Huntington Beach, CA. This organization is now owned and operated by Boeing. The most recent approved version is Revision B, dated June 28, 1996 [ref-2]. A change revision was made by Boeing, named SSCN 000904, which affected most of the paragraphs. This change notice is not dated. A draft of revision C also exists, but was never approved for use.

A cursory review of Revision B by GSFC identified significant problems with the specification and indicated that it does not accurately describe the physical characteristics and performance of the cable that is being used and does not adequately define the qualification requirements. The condition of the specification is not considered to be a leading cause of the failure of the cable. Team 1, described in the Background section above, may produce a new version, which will supercede all of these previous versions.

3.2 The Cable Design and The Performance Requirements Used

Two part numbers were defined in Revision B and the change notices: NFOC-2TFF-1GRP-1 and NFOC-2FFF-1GRP-1. The former was for a PFA jacketed and PFA buffered design and the latter was for a FEP jacketed and FEP buffered design. Table A-1 of SSQ 21654, Revision B., SSCN 000904 summarizes the optical performance ratings and cable component materials and dimensions, and is included here as Figure 2 and Table 1 below. The corresponding part number to Figure 2 and Table 1 is NFOC-2FFF-1GRP-1. A crossection is shown in Figure 3.

Find	Item	Dimension	Material	Construction
A B	Core Cladding	100 ± 2µm 140 ± 2µm	Doped Silica	Drawn
C	Hermetic Coating	0.025-0.05 µm Thickness	Carbon Based Hermetic Sealer	Chemical Vapor Deposition
D	Fiber Coating Buffer	170 ±2 µm	Polyimide	Coat with Heat Cure
E	Cable Buffer	380-760 ± 25µm	FEP-Teflon	Extruded
F	Strength Member	1.6mm OD	Teflon Impregnated Fiberglass	Braided
G	Cable Jacket	2.10 ± 0.05mm .25mm Thick	FEP-Teflon	Extruded

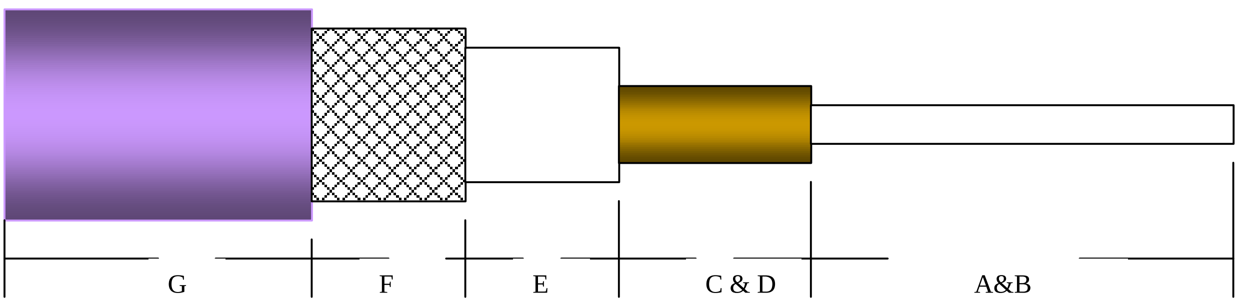
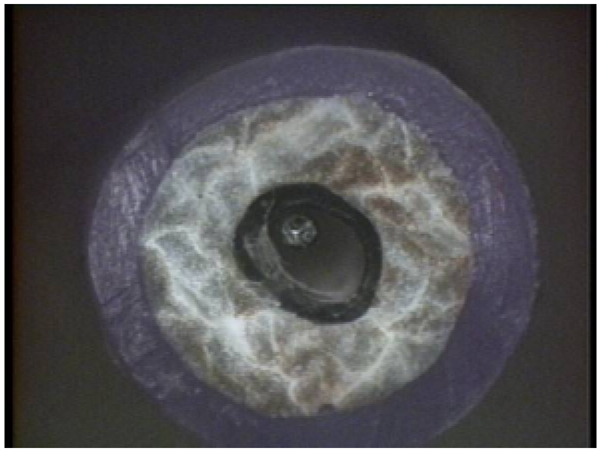


Figure 2 NFOC-2FFF-1GRP-1 Cable Design



Courtesy of NASA GSFC

Figure 3 Crossection of the NFOC-2FF-1GRP-1 Cable

Table 1 NFOC-2FFF-1GRP-1 Optical & Mechanical Characteristics

Characteristic	**From SSQ 21654, SSCN 00904**
Attenuation	4 dB/km @ 1290 ± 10 nm
Numerical Aperture	0.30 ± 0.02 @ 1290 ± 10 nm
Bandwidth	200 MHz-km @ 1290 ± 10 nm
Proof Strength	200 kpsi minimum
Core Ovality	5%
Cladding Ovality	4%
Core/Cladding Offset	98% minimum
Cable Weight	5.5 lbs/1000 ft. maximum
Color	Violet per Mil-Std-104
Temperature	Operating: -100°C/+75°C Storage: -100°C/+85°C

Order sheets were reviewed by Boeing and an inspection of the U.S. Lab was done by Boeing to understand how much of the NFOC-2TFF-1GRP-1 (PFA/PFA) cable may have been used in the U.S. Lab. SEA Wire and Cable (SEA) provided information about orders delivered for both the NFOC-2TFF-1GRP-1 and NFOC-2FFF-1GRP-1 cable. Table 2 shows the lengths of NFOC-2TFF-1GRP-1 cable ordered by several users.

Table 2 Deliveries of PFA Jacketed Cable

Invoice Period	**No. of Orders**	**Customer Name**	**Total length ordered (ft)**
8/11/93	1	MTP Aircraft	525
3/6/95 & 8/14/95	2	Boeing Huntsville	45
9/6/95	1	Spar Aerospace (CAE Electronics)	700
9/18/95	1	McDAC (Boeing HB)	5000
12/95	1	ITT Cannon	4500
3/30/95	1	Space Systems Loral (for Japan)	197
4/20/95	1	Standard Wire and Cable	434

The equipment inspection did not find any NFOC-2TFF-1GRP-1 (PFA/PFA) cable in the U.S. Lab. Evidence is not definite about the use of –2TFF- in ISS element Node 1. A list of Node 1 harnesses, prepared as part of another effort, indicates 1 harness containing 10 links is constructed of -2TFF-. The total length of –2TFF cable, per this list, is approximately 200 feet [ref-3]. The material delivered to ITT Cannon is believed to have been used in the development and qualification of the connectors used by ISS. NFOC-2TFF-1GRP-1 is no longer being used because its optical loss was found to increase after thermal cycling due to excessive shrinking of the PFA material (jacket and buffer shrinkage was not controlled by the specification requirements).

Table 3 in Section 3.3 shows the NFOC-2FFF-1GRP-1 cable delivered by the sole distributor, SEA Wire and Cable to various customers. BICC's shipping certificate of compliance references the cabler's internal part number, OC-1614, and contains a sentence at the bottom indicating that the cable was "manufactured to and acceptance tested in accordance with the SSQ 21654, and CR SSQ 21654-008".

SEA performed cable outer diameter (OD) measurements at each end of the reel as an acceptance measurement. For all other acceptance measurements, SEA used BICCGeneral generated "Certified Test

Data" to document the conformance of the cable to the specification requirements. Samples of these documents were provided by SEA and BICCGeneral. Ten of the 25 design characteristics reported by BICCGeneral are recorded on a go/no go basis; ten are referenced to a "Spectran" inspection, and five are shown as a measured characteristic. *["Spectran" refers to the fiber manufacturer, formally known as Spectran Specialty Optics Company and now called Lucent Specialty Fiber Technologies or Lucent-SFT]*. Several other identifying numbers are shown on the sheet including reel number, date, customer order number, BICCGeneral part number, Date of Manufacture (DOM) and length. The BICCGeneral part number used was OC-1614. A footnote at the bottom of the sheet indicates that the material is made and tested in accordance with SSQ 21654.

All of the requirements referenced on the test data sheet correspond to those listed in Figure 2 above. During a review of the processes used at BICCGeneral, the attenuation and cable layer dimensions measurements done by BICCGeneral were found to be in accordance with the specification requirements.

BICCGeneral ordered the fiber from Lucent-SFT in accordance with a build specification numbered BF04515. A review of the processes used at Lucent-SFT showed that they were performing optical and visual inspections correctly including fiber geometry measurements.

Issues were identified with respect to the manner in which the proof test is executed at Lucent-SFT. An industry standard proof test is defined by EIA-FOTP-455-31, Fiber Tensile Proof Test. This test method specifies that the user specified minimum tensile stress is maintained on the fiber for a minimum time of 1 second. Lucent-SFT's implementation of the proof test in-line with the fiber draw process does not achieve this dwell time. It was recommended that Lucent-SFT also add a bend in a fourth axis to achieve a test that exposed more of the fiber surface to the tensile load. Strength testing done by Boeing on virgin BF04515 fiber (never put through any of the cabling processes) showed results above 5 lbs.

The cable specification requires the fiber used to meet a minimum proof strength of 200 kpsi, (which corresponds to 5 lbs of tension for this fiber), though it does not detail how that strength should be established. Since in-line proof testing is fairly common throughout the industry, the EIA test method needs to be revisited to provide a high-speed test or to disallow it. The SSQ documentation will have to do the same.

Both the fiber manufacturer, Lucent-SFT, and the cabler, BICCGeneral, were found to be delivering product in accordance with the details shown in Figure 2 and Table 1 above with the exception that the fiber proof test was not achieving a 200 kpsi load on the fiber.

3.3 Indicted Stock

A review of all NFOC-2FFF-1GRP-1 cable delivered by SEA and BICCGeneral to Boeing-Huntington Beach (Boeing-HB) and Boeing-Kennedy Space Center (Boeing-KSC) was performed by examining the shipping records. Several spreadsheets were developed by each organization to summarize the findings. SEA provided information about lengths ordered, by whom and the date of manufacture (DOM) for the cable (and its shipment date). BICCGeneral supplied records including cable reel numbers, order numbers, DOM and some traceability to fiber lot. A great degree of inconsistency exists regarding the use of the term “lot” and as a result, several significant blocks of traceability data do not exist. Table 3 shows the amount of NFOC-2FFF-1GRP-1cable delivered by SEA.

Table 3 NFOC-2FFF-1GRP-1 Cable Delivered by SEA Wire and Cable

Invoice Period	No. of Orders	Customer Name	Total Length Ordered (ft)	No. of Reels*
6/12/96 & 7/26/96	2	MCDAC Huntsville	5031	8
6/26/96 to 12/30/98	14	ITT Cannon	7423	
7/17/96 to 4/1/99	14	Boeing Huntsville	40,695	41
7/19/96	2	CAE Electronics	500	
7/24/96 to 5/7/99	27	Boeing Huntington Beach	109,346	
7/25/96 to 11/25/98	10	Nakano Aviation	9453	
8/9/96	1	Amphenol	1200	
9/5/96 & 5/1/97	2	Space Systems Loral	8990	
11/15/96 & 2/17/97	2	Pacer	600	
3/26/97	1	NTK Aviation	1000	
5/28/97 & 4/7/99	2	Electronic Conn	701	
6/17/97	1	Standard Wire and Cable	100	
7/18/97 to 11/25/98	7	OHB Systems	11,596	
10/6/97	2	Boeing Downey	1496	4
1/23/98	1	TRW Components	168	
7/13/98	1	Boeing Seattle	100	
11/30/98 & 5/7/99	2	Lockheed-Martin Houston	600	
11/30/98 to 8/17/99	5	Boeing KSC	9575	8
12/16/98 & 7/2/99	2	Prime Cable	800	
1/20/99	1	Elymat Industries	89	
6/25/99 & 7/12/99	2	Undefined	400	

*No entry indicates number of reels was not researched.

Preliminary findings and discussions identified several significant periods in the production and use of the cable that were thought to be unique with respect to the number of defects found and the process changes made. The abruptness with which these types of defects surfaced seemed to indicate that some part of a once stable, validated, process had gone out of control. All of the cable delivered to Boeing and not already installed in the U.S. Lab was screened optically, with visual fault finders. Glows and echos were found in reels manufactured in 1998 and 1999. No 1996 era product was available for test until several reels in bonded storage at SEA, were returned to Boeing (these had been returned to SEA by Boeing for “out of specification” roundness). One glow, which was found to be a “rocket engine” defect, was found in one of these 1996, out-of-spec reels. No 1997 era cable was found for test.

Table 4 Shipments Containing Reels of Cable Found with Rocket Engine Defects

BICCGeneral SHIP DATE (always within 1 wk of manufacture date)	Cable Length Dlvrd to SEA (ft)	Number of Reels Screened*	Number of Reels Found with Defect(s)
12/22/95	545		
2/16/96	200		
6/12/96	1900		
6/17/96	1718		
6/18/96	640		
6/25/96	2555		
8/1/96	2655	5	0
8/29/96	6836		
9/26/96	22060		
12/19/96	7048	6	1
11/21/97	15574		
2/28/98	384		
7/21/98	4998	5	2
8/25/98	698		
8/27/98	9594		
8/28/98	3402	4	0
11/24/98	20044	1	1
3/31/99	15710	14	13
4/1/99	7092	9	7
4/30/99	20286	12	3

*No entry indicated and no screening performed on associated lot.

No uncabled fiber of 1996 vintage was available for examination. Five reels of 1998 BF05202 fiber, which had never been cabled, were available at GSFC through another flight project (BF05202 fiber uses the same preforms and draw processes as the BF04515 except that slightly different cladding and coating outer diameter specifications are used). No glows were found in these reels (~3,000 ft of fiber).

The links installed in the U.S. Lab were not each inspected with either a visual faultfinder or an OTDR due to the lack of equipment and manpower resources. This precludes determining the relationship between the quality of the installed cable and the quality of the samples that were available for test, but were of a different manufacturing period.

Oral histories were taken from people involved in the assembly of the harnesses used in the U.S. Lab. The technicians indicated that there was an unusually high amount of scrap but that it wasn't considered high enough to stop production for failure analyses. The failures were attributed to handling, which may have been a logical assumption for a team new to working with fiber. It may also have been the result of an inadvertent defect screen. Some breaks were found in integrated harnesses in the U.S. Lab but they were typical of failures due to overstress at connector backshells.

The "rocket engine" defect in the 1996 cable and the speculation that some "rocket engine" defects may have been discarded in the scrap associated with the U.S. Lab harness builds, caused the team to suspect that the "rocket engine" defect and the low strength failure mode was ubiquitous to the NFOC-2FFF-GRP1-1 cable.

4.0 MANUFACTURING PROCESSES

The manufacturing processes used by SEA, BICC and Lucent-SFT were discussed regularly during the investigation. Reviews at each of the respective plants (two for Lucent-SFT) were performed in order to understand the processes being used and their possible contribution to the creation of the defect.

4.1 Distributor

Boeing-HB led the review and performed a data traceability review for six NFOC-2FFF-1GRP-1 1996 era cable reels. Some records were found while others were not. SEA processing required only measuring OD, cutting cable to length (including a respooling process) and re-labeling the spools of cable received from BICC. All cable shipped to Boeing-Huntsville (Boeing-HSV) was respooled to plastic reels from wood reels. There were no processes found at SEA to be damaging the cable and causing the rocket engine defect.

4.2 Cabler

BICC generally delivered the cable to SEA within six days of its manufacture. Twenty (20) deliveries to SEA were made between 12/95 and 4/99, mainly centered around: the second half of 1996 (46 kft total), 11/21/97 (15 kft), 10/98 (39 kft), and 4/99 (43 kft). The records show no production other than these four periods.

A comparison of the shipment records to the reels identified with the “rocket engine” defects did not clearly show an abrupt increase in defective cable corresponding to large changes in either production volume or cable length. There were distinct periods of high throughput and shipment of multiple short lengths. A review of some of the corresponding purchase order information indicates that the short lengths were not specified by the buyer.

The processes given the most attention during the review at the BICC facility were the records keeping, fiber respooling, extrusion and the optical measurement processes. Later discussions focused on the extrusion process because findings were revealing that the extrusion conditions were very likely causing a generation of HF which acts as an etchant when it contacts glass.

4.2.1 Record Keeping

Records for six reels of cable were exhumed. Most of the materials traceability was not recorded. A buffer run sheet, which specifies manufacturing settings/conditions and specifications for a given product, is provided to the extruder operator to record the events of the run. These sheets were not filled out properly for the reels of interest, more so for the 1996 timeframe. The record keeping has improved over the period that the NFOC-2FFF-1GRP-1 has been made at BICC, however it is still not sufficient to show a complete traceability history. There is no fiber traceability, for example, for most of the reels made in 1996 – the vintage used to populate the US Lab module.

4.2.2 Storage and Factory Environment Control

“The environmental conditions of the extrusion facility were kept to 21 to 24 degree C and 45% to 50% relative humidity. Fiber storage was controlled in a separate area with limited access. The cable manufacturing location, containing two extrusion lines, were also outside of the general walking traffic. All processes following re-spooling and fiber storage were performed in the same room.

4.2.3 Respooler

Correspondence records supplied by BICC showed that in January of 1997 McDonnell Douglas (Now Boeing-HB) notified them that the polyimide coating on the fiber in the NFOC-2FFF-1GRP-1 cable, was dimensionally out-of-specification. This was confirmed by Boeing-HB personnel who were not able to terminate the fiber in the connector ferrules because its outer diameter (OD) was too big (following return of the product it was realized that the wrong fiber part number was cabled and shipped). Between 3/97 and 10/97 arrangements were made to use a LaserMike™ laser based measurement device installed on a fiber coating machine to screen the fiber for out-of-spec OD. This equipment, a Nokia OFC52, was normally used to add colored coatings to fiber for identification purposes, and is often referred to as a color-line. Use of this system as a screen was first used on 10/7/97 and became a permanent process for the NFOC-2FFF-1GRP-1 cable thereafter. Adjustments were made in April of 1998 to resolve calibration issues.

The respooling process was considered a possible source of ESD that could be damaging the fiber. A discussion of the susceptibility of the polyimide to breakdown and subsequent current flow in the carbon coating is presented in Section 6.1. Electrostatic field measurements were made during a respooling operation on the color-line using the BF04515 polyimide/carbon coated fiber (the ambient relative humidity was 45%). Two meters were used, a 3M 709 Static Sensor and a Plastic Systems 42720 Static Field Meter. These meters are intended for measuring fields extending from charged, flat plates. At the time of the release of this report, agreement was not reached regarding the interpretation of the measurements recorded and shown in Table 5 because the geometries that were measured were varied and not plane sources.

Table 5 Electrostatic Field Measurements Taken Around “Color Line”

Location	**Field During 20 m/min operation (V/inch)**	**Field During 50 m/min operation (V/inch)**	**Field During 20 m/min operation (V/inch)**	**Field During 50 m/min operation (V/inch)**
	3M 709 Measurements		Plastic Systems 42720 Measurements	
Let-out reel	+40	+25	-200	+640
1st pair of tension control wheels	+30	+110		
Pre-ionizier wheel	-2000	> -10,000	+350	N/A
Post-ionizer			-980	-900
Entrance into wheel/belt section	-140	-1150	-300	-3500
Exit out of wheel/belt section	-35	-65		0
Pre-OD detector				-500
Post OD detector	-25	-45		
Take-up reel	+85	+50	+50	-300

4.2.4 Extruder – Buffer and Jacket Processing

BICC demonstrated the operation of the extruder after the FEP pellets were added and melted in the reservoir. The original shipping containers were kept near the secondary containers, which showed the color of the pellets and were marked with the name of the material. The conditions for heating the pellets, the extrusion temperature, and the extrusion rate were reported by the process engineer. No special precautions were taken to avoid creating corrosive decomposition products from extruding in air such as baking out the pellets and confining the extrusion atmosphere to something other than air. Temperatures ranged between 288°C (exposure to air following extrusion) and 404°C during the extrusion process.

Immediately following extrusion, the cable passes through two water baths. The same process, with a different extrusion head, is used when applying the jacket. The extrusion line was reviewed with the field meters the results of which are shown in Table 6.

Table 6 Electrostatic Field Measurements Taken Around the Extrusion Line During a Buffering Operation

Location	**Field (V/inch)**
Let-out reel	-750
Air space between quenching baths	-150
Exit of second quenching bath	-10
Length counter (wheel & belt)	*
Rubber belts – entry	-110
Rubber belts – exit	-45
Tension wheels – 1st	+2000
Tension wheels – 2nd	+2250
Tension wheels – 3rd	+75
Ground chain	-100
Metal feeder wheel	+305
Take up reel (in path of de-ionizing fan)	-1500

* Did not capture numerical data but recollection is that it was near the minimum floor of 50V/inch.

4.2.5 Strength Members

The equipment and materials used for applying the braided strength members to the buffered fiber were briefly reviewed and found to be industry standard with no detail that seemed related to the fiber failure. BICC reported that the only time they rejected finished NFOC-2FFF-1GRP-1 cable was when lumps were found under the jacket due to the strength members (associated with the change out of a spool of the strength member material, Teflon™ impregnated fiberglass). Lengths with this defect were cut out and not delivered to SEA.

4.2.6 Optical Measurements

Both a Tektronix™ TFP2 FiberMaster and a GNNettest™ CMA 4000 are used, at 1300 nm wavelength, for measuring attenuation. The equipment and set-up were witnessed and nothing was found that would indicate incorrect measurements were being recorded or that the method being used contributed to the fiber defect. BICC reported that they had not rejected any reels of cable based on optical performance.

4.3 Optical Fiber

Great attention was also paid to the details of the fiber production processes in order to understand the root cause of the defects and if any conditions were found which could isolate them to specific lots or periods of production.

4.3.1. Raw Materials for Preform Manufacture

Lucent-SFT makes their own glass preforms. The applicable raw materials are the natural quartz cladding tubes and the gases. The gases are monitored for quality on an incoming sample basis and are monitored daily, in-line, for water content. The tank farm for most of these gases (some come in transportable cylinders) was moved between 1996 and 1997. There was no strong evidence indicating that the move of the tank farm or the handling of the gases allowed contamination of the gases or contamination of the preform manufacturing processes.

The pure fused silica substrate tubes are reviewed for defects and records are kept allowing traceability between the raw material and the finished preform. Many of the preform build records showed a great degree of "flaws" in the tubes however this is normal in natural quartz. These features in the received quartz tubes have not been connected with the "rocket engine" defects or the low break strength and have not been investigated further.

4.3.2 Preform Fabrication

The BF04515 fiber is drawn from preforms uniquely identified by a part number containing the number 320-R. All "320-R" preforms are made on one lathe, which is reflected in the preform part number. This lathe is also used to fabricate several other preforms whose recipes use all of the same ingredients as those used for the "320-R" product or a subset thereof. The "320-R" preforms are also the originating material for several other variations of fiber dissimilar to the BF04515 only in the glass and coating tolerances. The "320-R" lathe is located apart from the main production area in an area reserved for R&D activity, is air-conditioned and is humidity controlled. R&D operators are selected from the experienced pool of operators who make standard Lucent product.

The build sheets include requirements for the gas mixture, the process recipe and spaces for recording observations and process variations. Tweaking of the process recipe is allowed within engineered specified limits and is performed by the specially trained preform technicians who run the equipment and monitor the fabrication run. When a slight change is made for this purpose, it is saved as part of the current preform recipe. The recipe revision in place during each preform run is recorded on the build sheet. That recipe revision will stand until another change supercedes it. The dimensions of the finished preform and defects or features, such as bubbles and airlines, observed in the preform are also recorded. A refractive index profile is measured for each preform in a separate laboratory. An example of one is shown in Figure 4 [ref-4]. The "MESA" database is used to link the preform records with the records for the finished fiber. This automated filing system was started in the second half of 1996. A paper system predated the use of the "MESA" system.

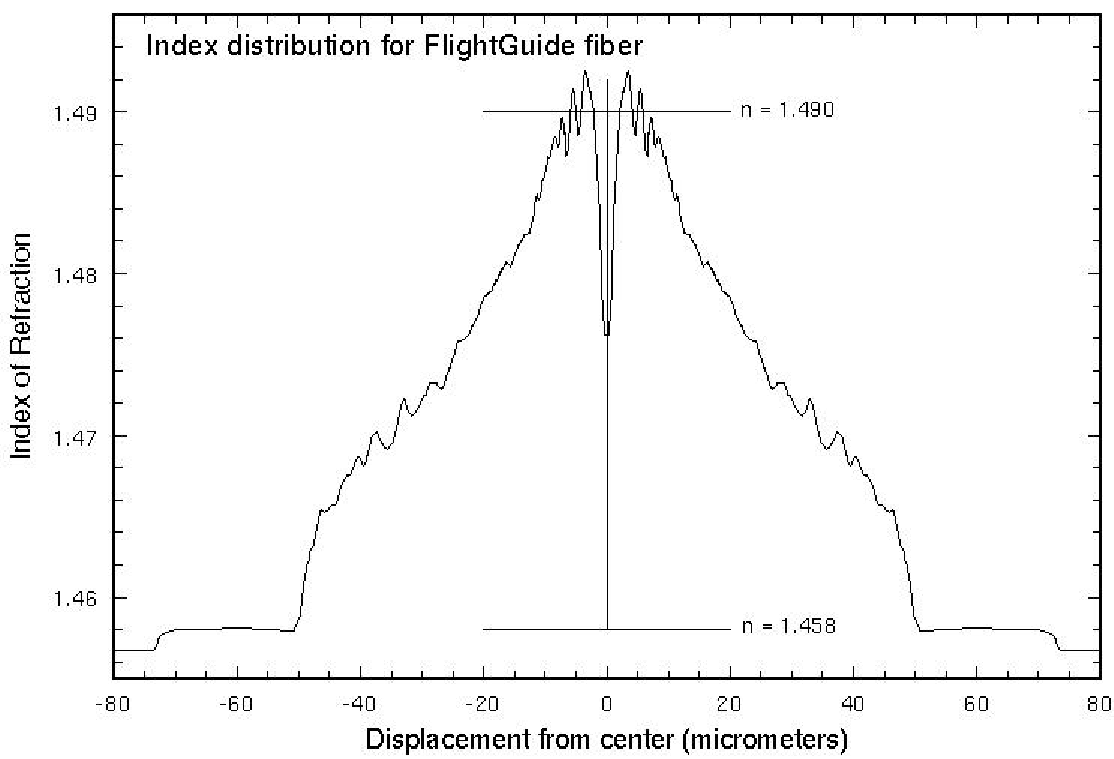


Figure 4 Preform Index Profile

Preform processing includes cleaning and etching the substrate tube and the finished preform. Both a hydrofluoric acid bath and fire polish are used. These methods along with the CVD method for growing the core/cladding transitional layer and the core, eliminate the possibility that contamination was trapped between the core and cladding, inside of the core or in the surface of the cladding layer of the preform. The creation of a void inside of the preform due to an inside contaminant could only take place during the major neck-down of the preform during the fiber draw process. This would produce a defect elongated by at least some significant fraction of the drawdown ratio, which is approximately 12,000:1 in the longitudinal direction. This amount of elongation is quite the opposite of the shape of the radially elongated, bulb shaped defect that is the subject of this report.

A review of the preform records showed manufacture of 181 "320-R" preforms between 11/94 and 8/98, the heaviest period of production of being between July of '96 and April of '97. Of these 181, 17 were traceable to NFOC-2FFF-1GRP-1 cable. Eight were associated with reels found with a "rocket engine" defect. All preforms used for the Boeing fiber were produced prior to August of '98, and were held in stock up to a year before they were drawn into fiber.

4.3.3 Fiber Manufacture

A review of the fiber draw and cabling facility in Avon, CT was performed. Though the traceability between the cable and the fiber is not complete for much of the pre-1997 cable, the records indicate that at least 81kft of fiber in the NFOC-2FFF-1GRP-1 cable was drawn at the current facility and 53kft was drawn at a facility which has since been decommissioned. The fiber drawn for the NFOC-2FFF-1GRP-1 cable is called BFO4515 by Lucent-SFT.

The current facility, at Darling Drive in Avon, CT, contains several draw towers although all of the BFO4515 fiber was drawn on a single tower that is part of the fiber reel number. The draw room is temperature controlled to around 22°C and limited to traffic through a clean-room entrance (approved personnel only, smocks required, etc.). An auxiliary glass lathe for fire polish is kept in the same area as the draw tower. In-line and end-of-line test equipment are run along side the tower controllers and computers.

The build records start by instructing the draw operator how to manually set the tower settings which include draw speed, iris settings, gas flows and cure temperatures. A two-axis laser based micrometer is used with an active control feedback to the glass furnace. The control loop allows real-time adjustment of the draw speed in order to maintain the required glass outer diameter. The reactor for the carbon coating is located immediately below the draw furnace, which is at the top of the tower. The polyimide coating is applied in several stages below the draw furnace. The polyimide forming material is delivered to the coating applicator cups. Coating die size, incoming fiber size, draw speed, and material viscosity (temperature controlled) determine the actual volume per unit length deposited onto the fiber. The coating application dies are fabricated from specialized materials in order to preserve the ultra high precision required over multiple draws.

The draw operator looks for defects in the coating as an in-line acceptance screen during draw. Coating defects are inspected visually and by "feel". A LaserMike™ -based, four-axis inspection system is in place in-line to detect coating thicknessess out of specification. This second set of laser micrometers do not have an active control loop with the coating process. They trigger an alarm when the geometry limits are not net and the draw operator must react appropriately.

All of the BF04515 fiber was proof-tested in-line during the draw/coating process using a 3-plane mandrel system. Lucent has recently increased the number of mandrels/planes to 4. The review team is not in agreement regarding the proper execution of an in-line proof test that will expose the coated fiber to a minimum 200 kpsi for a minimum length of time. Recommendations about how an in-line proof test should be done, will be submitted under separate cover to the EIA/TIA for inclusion in the standard test method.